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Simulation of the Qaraoun Reservoir Operation with regard to the Effects on the whole Litani River System in Lebanon

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Abstract

Lebanon, a country in a semi-arid region of the middle east, in previous times relatively rich in water has to reassess their water resources management due to increasing and changing demands. The most important River System in Lebanon (regarding the availability and quantity of water) is the Litani system, which was studied in the frame of this work. The main storage facility within the Litani project (initiated in the early 1950's), the Qaraoun reservoir has a capacity of 220 MCM. Although it was originally planned as a multipurpose facility, releases of the reservoir have been almost only used for hydropower production since it went into operation. Nevertheless because of the increasing water scarcity and new demand areas the allocation of the available water resources need to be reviewed and the operation policy of the reservoir has to be reassessed. A simulation model, based on historical inflow records has been developed and serves to study different scenarios with different operating policies. The simulation and its results of single – as well as multi – objective water use scenarios are performed to investigate a) the effects of new projects of different water sectors (domestic as well as irrigation) on hydropower production and b) the yield of the present and possible future system configuration.

Introduction

The Litani River's Qaraoun Dam was the countries most ambitious water project, which was conceived by Ibrahim Abdel-Al some 50 years ago. Ibrahim Abdel-Al's vision was a simple one. An electrical engineer and hydraulic specialist, he believed that Lebanon had both the means and the talent to create a water management system to ensure that the country never runs out of its most valuable resource. "Water is a source of live and a fountainhead of civilisation. It forms the basis of reconstruction and is directly linked to prosperity," he wrote in 1947 (Khayyar Munira, Al-Awar Nada, 2000). Acutely aware of the water shortages likely to confront other countries in the region in the future, Mr. Abdel-Al's plans for his native Lebanon centred around the Litani River, which he often described as "Lebanon's living artery".
In 1966 the first stage of the so called Six-Years-Plan, which was already commissioned at the end of the second world war and included the river Litani and four other major rivers of Lebanon, was implemented. This contained the Qaraoun and the Awali system. During this time already competition among Lebanon's agricultural, industrial and municipal sectors began to increase. Municipal use was stimulated by the rapid growth of the countries' urban centres in the post-war era. The sectarian system of Lebanon has to be considered to fully understand why only parts of the master plan have been implemented while other until now have been abandoned. Kolars (1993) states that during the early years of the implementation the

urban live was politically controlled, and hence dominated economically as well as culturally, by Christians and Sunni Muslims. This situation was created partly by the use of the Litani to generate hydro-electricity, which enabled the rapid development of the industry and business, but at the expense of agriculture in the south of Lebanon. Thus during the decade of the 1960s, the high living standards of Lebanon's urban population was tied directly to the policy decisions made for the use of the Litani River. Prior to the civil war, an intense effort was made to work out a comprehensive management scheme for the Litani. The result of this was the beginnings of a unified system of resource management in South Lebanon. This effort was formalised by the government of Lebanon through a degree which defined the disposable water resources and set the priorities (and water rights) accordingly. This unique decree for Lebanon was never implemented.

The decade of civil war brought the country even backwards and as Murakami et al. (1994) stated, "when peace does come to Lebanon, and developmental pressure resume, there will be an increasing internal demand placed on the reserves of the Litani river."

Because of that during the last decade water allocation is shifting from hydropower production to other demand sectors. Due to the increased demand of energy in Lebanon the share Hydropower production in the energy sector has declined in the last decades from 75 per cent to 8 per cent although the allocation of water for hydropower production remains the same. The most widely used response to the dynamic of the region with its changing demand is to modify the operation of existing facilities, perhaps with modest changes in the region's physical water infrastructure and modification in water demand and water allocation.

Furthermore in arid and semi-arid regions like Lebanon it is generally not economically feasible to develop and operate a water resource system to meet all demands at all times. Supply restrictions become on eof the few management tools the operator can use in order to cope best with the exploitation of such highly variable streamflow conditions (May, 1996).

Objectives

The performance of the Litani River system has been simulated considering different scenarios. As a first step the system configuration has been investigated and described to get detailed knowledge about current and possible future demand in time and space.

Two extreme operating policies will be simulated and discussed. The models that are used to carry out these simulations have been particular developed for the Litani river system with the Qaraoun reservoir and the Bisri reservoir (see figure 2), planned for the future. Actually two models are required to compare the optimised present energy output (single – purpose) with the potential energy production when the Qaraoun reservoir will be used as multipurpose facility.

Additionally to the evaluation of the energy output, the whole systems yield will be investigated to find out if the future demand of the different sectors (Domestic, Irrigation and Hydropower) can be satisfied.

This is done by analysing the following four different criteria:

- The quantity – based reliability
- The time – based reliability
- The vulnerability, which is a measure of how severe the consequences of failure may be, measured in square shortages of the demand
- Sum of failures in percentage of the system performance concerning spill (quantity and frequency) and violation of the dead storage level which should be maintained throughout the year.

Analysis Methodology

The analysis methodology used herein is the so-called operational analysis. It resolves issues related to the operational strategy of a water resource system and investigates the performance of a static (snapshot in time) system. The operational analysis may consist of water resource allocation decisions evaluated by a reliability criterion or an economic criterion.

The developed model is focused on the best possible short-term utilisation of the resource. "Short-term" has to be understood as real-time operation, which is especially important, where resources are highly utilised and where all demand cannot always be met. The structured curtailment of supplies then needs to be implemented in such a way so as to prevent the supply system from total collapse with possible severe consequences.

Two basic approaches can be followed with respect to devising real-time operating strategies. These are simulation analyses based on a predetermined hierarchy of decisions, and optimisation techniques with a specified objective function.

For this study the first approach is used. Additionally a feature to optimise an objective function is implemented (by manually trial and error). It aims to minimise the square shortages, which might occur in dry years. In other words reliability of supply is a basic decision criterion to ensure that future supplies are not jeopardised in favour of meeting current demand, but to aim at an equitable distribution over time (here done by hedging).

The operational rule is always to supply the high priority demand first, followed by the other priority classes in declining order of importance.

System Model

A model represents the whole simulation process by mathematical equations.

The state equation describes the transition of the system state from the beginning of a certain stage to the end of that stage, as affected by inputs and operational decisions. These operational decisions are taken on certain variables (decision variables) that can be controlled by the decision-maker. The system equation (mass balance equation) that represents the state of the system at the beginning of time stage t and at its end t+1 can be written as follow:

$$S_{t+1} = S_t + I_t - R_t - L_t - Sp_t \qquad (1)$$

Subject to:

$$S_{min} \leq S_t \leq S_{max} \qquad (2)$$

$$R_{min} \leq R_t \leq R_{max} \qquad (3)$$

St State variable: represents the reservoir storage in the beginning of the current discrete time step t

Rt Decision variable: controlled variable that affects the state of system and can be decided on, here the release out of the reservoir in the current time step

It Inflow in the reservoir in the current time step, uncontrollable variable

Lt represents the sum of the reservoir losses during the current time t, mainly evaporation and/or seepage.

Sp_t Spill, see next page

Evaporation $Evap_t$ [MCM] is an uncontrollable variable and considered as a function of the average reservoir surface area during time t, which in turn is a function of the average storage during the same time:

Where:

$$Evap_t = E_t \cdot \left[A(S_t) + A(S_{t+1})/2\right]/100000 \quad [MCM]$$

A(S) is the surface area of the reservoir at a certain storage level in ha. The presence of the next month storage term requires an iterative solution, which is done by the program itself, E_t is the evaporation rate during time step t (mm/month)

Sp_t Spill (uncontrolled output) during time step:

$$Sp_t = \begin{cases} 0 \quad \text{if } S_t + I_t - R_t - L_t \le S_{max} \\ (S_t + I_t - R_t - L_t) - S_{max} \quad \text{if } S_t + I_t - R_t - L_t \ge S_{max} \end{cases}$$

At each time step t a decision is taken on the release R_t based on the simulated operational policy, and the end-of-stage S_{t+1} is calculated by equation (1).
The calculated value of S_{t+1} represents the start-of-the month storage in the next time step calculations.

Indicators for system failure
The following indicators has been used to evaluate the extend of systems failure.
Shortage (Sh_t): Calculation of reliability in volume and time

$$Sh_t = D_t - R_t \qquad \begin{cases} Rt \le Dt \\ \text{otherwise } 0 \end{cases}$$

Loss function: $L(Sh_t) = Sh_t^2$

Spill: If this calculated S_{t+1} is greater than S_{max}

Minimum storage failure: $S_{t+1} < S_{min}$

In the case of minimum storage failure the next month storage is set at the minimum storage and the release is adjusted accordingly, if possible. If the release calculated is a negative value, this negative amount has to be equalised, so that the storage at the end of the time step S_{t+1} might be smaller than S_{min}. In all cases, the event is recorded as a failure. The number of times this happens during a simulation period reflects the failure percentage, which is an indicator of the systems reliability.
Another reliability indicator is the ability of the system to satisfy the water demand. Failing to do so within the defined constrains is also counted as a system failure. The magnitude and time distribution of these failures is used to evaluate the efficiency of the simulated operating policy. The tested operating policy is usually assessed based on its ability to satisfy the systems requirements without violating any of the system constraints.
In this study two different indicators for satisfying the water demand (D_t) are used: shortage and square shortage (or deficit index). This distinction makes it possible to have an indicator for the severity of the occurred shortage.
Whereas the sum of the shortage of one simulation time horizon (here one year) can be the same for different policies, the sum of the square shortage Sh_t^2 gives an idea about the distribution of the shortages (the bigger deficits are given more weight) and therefore the severity of the systems failure.
An operating rule which uses the deficit index approach to put more penalty (or more weight) on large deficits than on small deficits is called “hedging rule”. By using this rule some deficit are induced earlier than they would normally occur to prevent massive deficiencies later.

The hedging rule is developed by defining a “critical/buffer storage level” $V_{cri} > S_{min}$. The model tries to release all demand: $R_t = D_t$, if $S_t < V_{cri}$
In case the remained water cannot meet the demand, only a certain fraction of the demand (or percentage demand satisfaction) is released.

$$R_t = \alpha * D_t \qquad \left(0 < \alpha < 1\right)$$

The amount of the demand satisfaction is chosen by trying to minimize the sum of the Sh_t^2 of the simulation period (one year). The deficit or shortage is calculated as follow:

$$Sh_t = D_t - \alpha\, D_t = (1-\alpha)\, D_t$$

In the developed model only one α per dry year (where shortage occur) can be decided on. This variable is one of the decision variables of the model as well as $V_{cri.}$ Important is to notice that still the mass balance equation is the basis for calculation.

System configuration

The map shows the location of the Litani system in Lebanon, the following schematic illustration describes the system configuration.

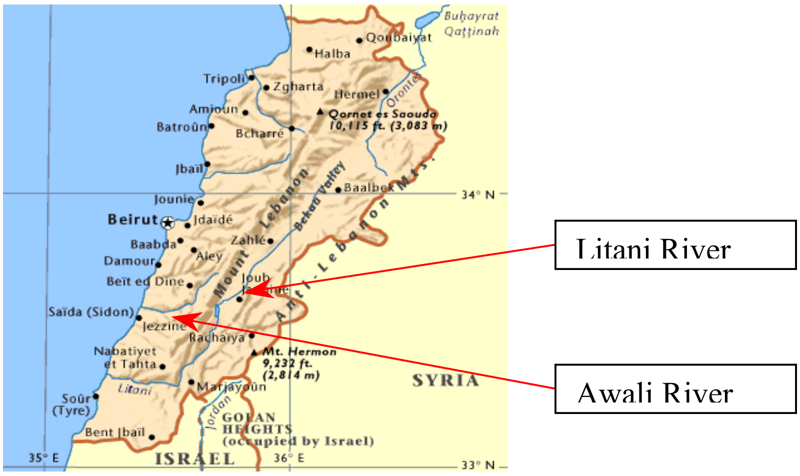


Figure 1: Map of Lebanon with its main rivers

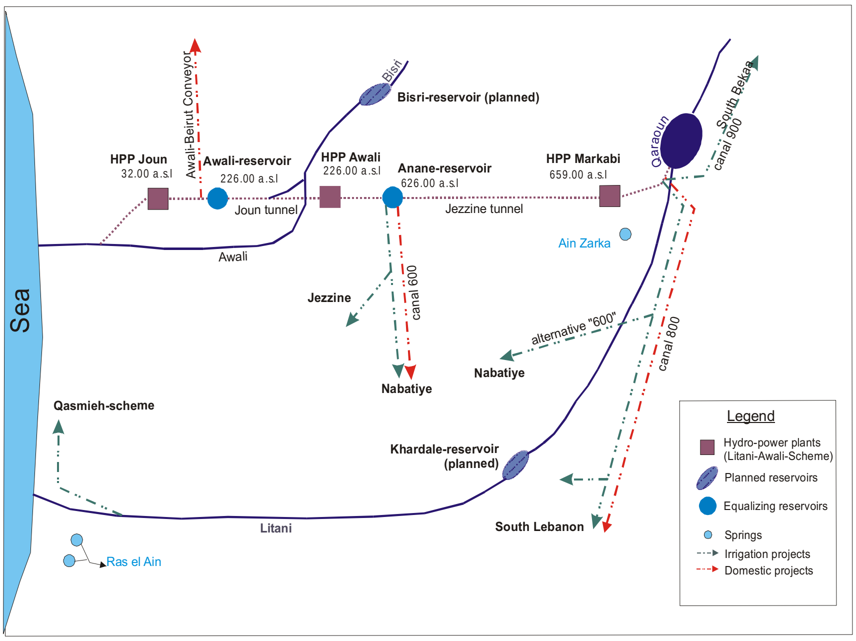


Figure 2: System configuration, current as well as planned projects

Data Processing

Daily records of inflows, releases, and storages for 34 years from 1966-1999 for the Qaraoun reservoir were obtained from the Litani Authority. The data were converted to monthly values to be compatible for use within the developed simulation model that works with monthly time steps. Historical data on evaporation rates was lacking. For this study evaporation data was taken from an privious study in which they were calculated from average climatic data (Climatic Atlas of Lebanon, 1967) using the Penman method (Jaafar, 1999).

Available reservoir data (provided by the Litani Authority) gives storage for each elevation of water in the reservoir above sea level. These data were used to find the Head – Storage, Area – Head and Area – Storage relations, necessary for Hydropower and evaporation calculations.

Additional the historical data were used to generate statistically inflows for the next 30 years, to be able not only to perform deterministic but also at least one stochastic simulation run. Here autoregressive modeling for periodic hydrologic time series have been used (Salas J.D. et al, 1988). For the generation of the hydrologic time series for this study an AR (1) – Model with periodic parameters is used.

Model Formulation

The developed models can be subdivided in two groups: single and multi – purpose simulation models. The single – objective simulation models were developed to get an insight into the systems behaviour and to calibrate the model with the comparison of the model output (hydropower production) and historical data received from the Litani Authority. Furthermore it is known that the operation of the reservoir has never been optimised. The second model therefore uses optimised operation rules (Jafaar, 1999) to obtain afterwards the real “loss” of hydropower production due to the implementation of the planned projects.

Altogether four scenarios were tested. The first and second are single-purpose scenarios. In the first only hydropower production is considered. This has to be done in order to compare the current energy output with the result in case the optimized operation policies will be employed. Scenario two is used to study the influences of the implementation of the irrigation projects only. For allocation of the available water some basic assumptions had to be made, this includes mainly a ranking of lets say a priority order for the irrigation projects in times of water shortages. Scenario three combines irrigation projects and potable water supply. The last scenario is a multi-purpose simulation and includes irrigation projects, potable water supply and hydropower production. With this scenario it is hoped to be able to evaluate the reliability of water supply for the different sectors for the future situation. Here hydropower production during the month is allowed only when there is no shortage in water supply for domestic and agricultural use in this month (full utilization policy). The other possibility is to use only the secondary yield of the system to calculate additional hydropower without the risk of violating the supply for the next month. Because this policy does not induce any additionally shortages to the mandatory ones, it is called “sustainable use policy”.

Results and Discussion

The following average draft – yield response diagrams are a graphical summary of the yield behavior of the reservoir/system. They help improving the understanding of the systems yield. It is desirable that the yield should be equal to the target draft. When the storage level is low, the yield may be reduced to less than the target draft. It is also possible to increase the yield when the reservoir is spilling (here for hydropower production). The extent of this increase depends on the installed abstraction capacity of the reservoir and on the ability of the destination user to make use of a variable water supply.

The first diagram shows the response of draft and yield regarding only the Qaraoun reservoir It has been determined by simulating scenario two and three, which have different target drafts.

The total demand of the scenarios have been considered, regardless whether they were fed only by the Qaraoun reservoir or by additional sources. Therefore one has to be cautious evaluating them. Diagram 1 gives only information about the yield of the reservoir. The total yield of the system is higher as additional sources can be utilised for the water supply. This phenomenon is shown in the second diagram.

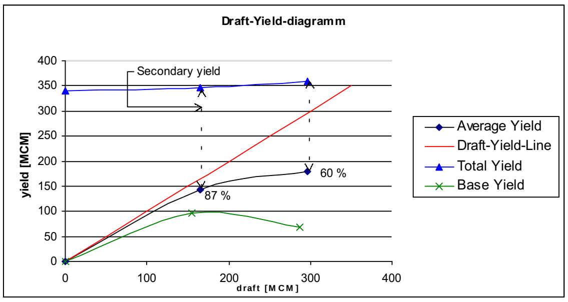


Diagram 1: Draft-yield response diagram (only Qaraoun)

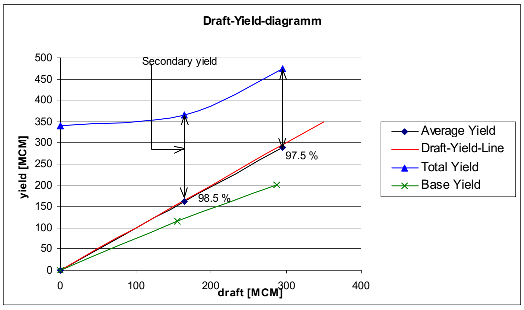


Diagram 2: Draft-Yield diagram, all sources

Secondary yield should in practice obviously be abstracted only if it can be used effectively. In the Litani – Awali system the whole amount of secondary yield can always be used to produce hydropower, which is still the cheapest way for energy production. Looking at the secondary yield it is important to notice that average values over the whole year are shown in the graph, which means that in wet years during the winter season a lot of spill may occur, whereas during the summer shortages may emerge. Summarising the results of the yields obtained only by the Qaraoun one can notice, that the base yield is already decreasing and the average yield much less increasing while trying to satisfy higher demand. The reason is because the capacity of the system is already reached and even exceeded.

Diagram 2 indicates a positive bottom line. The average yield line almost meets the draft-yield line, which is in fact the target draft. The simulation of scenario 2 meets the demand averaging to 98.5 %, scenario 3 is close to 97.5 %. Considering higher demand one could speculate that the system can still offer some buffer capacity since the decrease of the yield between the target draft of scenario 2 and 3 is very low. Furthermore the base yield even if it is not meeting the demand in the worst case is still increasing. This means that the upper limit of the systems' yield, with the systems configuration as planned for the future (new dam in the upper part of the Awali) has not been reached yet.

Only two more results can be shown. One is the amount of Hydropower which still can be produced by utilizing the reservoir in a multipurpose way. The result shown in diagram 3 has been calculated using the "sustainable use" policy, compared with the power production of scenario one. By using the full utilization policy, a more evenly distribution can be observed (diagram 4). The power production follows the same pattern than the sequence of the storage level. In diagram 4 can be observed that the system violates the Smin constraints as well never reach the full capacity. Since this are average values these two facts are an indication that shortages may occur in the drier months.

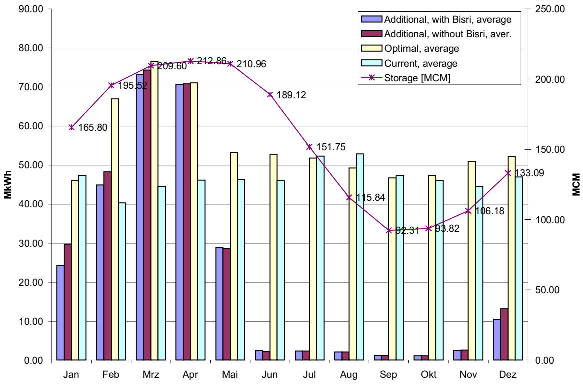


Diagram 3: Comparison of average additional hydro-power production of sc. 4 and 1, with average storage level during the year (sustainable use).

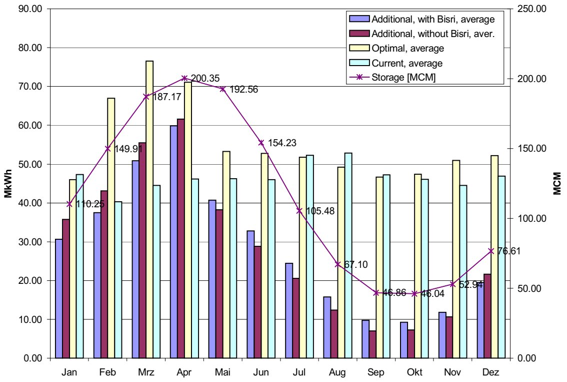
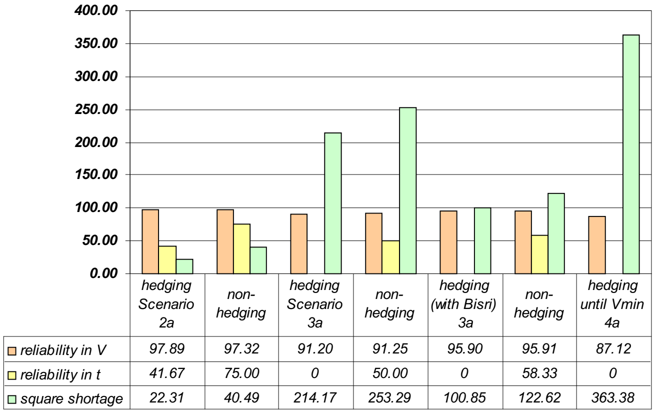


Diagram 4: Like diagram 3 with optimal use policy

The next diagram shows the reliability of supply and the square shortages of each simulation of scenario 2 until 4.



	hedging Scenario 2a	non-hedging	hedging Scenario 3a	non-hedging	hedging (with Bisri) 3a	non-hedging	hedging until Vmin 4a
reliability in V	97.89	97.32	91.20	91.25	95.90	95.91	87.12
reliability in t	41.67	75.00	0	50.00	0	58.33	0
square shortage	22.31	40.49	214.17	253.29	100.85	122.62	363.38

Here the results are shown when only considering dry years. In the multipurpose scenario the square shortage is relatively high, this indicates a high vulnerability of the systems loss. The results imply a low performance concerning demand satisfaction of water supply. This leads to the conclusion that it might be advisable to operate the system in favor for water supply since this is the main priority for the next decade.

It is worth mentioning that in the final stage using the *sustainable utilisation* policy (years with average and above average inflow) no shortages occurred during wet years. The time – based and quantity – based reliabilities always equals one, which means that with 100 per cent of satisfaction, no shortages will take place. However, in drier years the system will not be able to satisfy the demand until the full extension, but the reliability will still be around 0.95 on average.

Conclusions

Results show that the Qaraoun reservoir could be used efficiently for all demand sectors. The alternative configuration with the Bisri dam construction performs best, but still the system cannot cope with consecutive low flow years. Possible extensions of the old and preliminary plans would push the system even more to its limits. All this leads to the conclusion that the emphasis of water management has to change from increasing supply to improving supply reliability.

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